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DETROIT

# Abrasive Jet Method for Organic Coatings

## Rapidly Measures Abrasion Resistance

A SIMPLE, rapid method for measuring the abrasion resistance of organic coatings on metals has been developed by A. G. Roberts, W. A. Crouse, and R. S. Pizer of the National Bureau of Standards. Essentially, the method determines, under controlled operating conditions, the time required for a high-speed jet of fine abrasive particles to abrade through the coating to the substrate. Development was sponsored by the Navy Bureau of Aeronautics in connection with a program for the production of highly durable, scuff-resistant finishes for naval aircraft. Because the instrument readily simulates a variety of service conditions, the NBS procedure can be used to determine abrasion resistance on all types of protective coatings, regardless of gloss, color, thickness, or surface area.

Abrasion resistance is often one of the most important factors in the service performance of protective coatings. Until recently thoroughly reliable methods for determination of this property have been lacking. Several abrasion test procedures are available in which loose particles fall, rub, or are blown against the test specimen. Although the NBS abrasive jet method is similar in principle to these methods, it permits greater ease and rapidity in evaluating materials and better reproducibility because it does not depend upon abrading an area of definite size and uses a continuously fresh supply of abrasive particles under closely controlled conditions. The end point in this method is the first show of bare metal and is readily detected when coating and substrate differ in color, as is usually the case; otherwise, inspection with a hand lens can be used.

In the abrasive jet method, carbon dioxide gas under controlled pressure propels an abrasive powder from a vibrating storage chamber through a nozzle to impinge at high speed upon the test specimen. A solenoid valve operated with a manual switch turns the flow of the abrasive powder on or off. The mounting arrangement for the test specimen and nozzle assembly permits a rotational, back and forth, or up and down adjustment, while the angle between the nozzle tip and surface to be abraded is adjusted by a graduated rotating disk attached to the nozzle shaft. A specially calibrated taper gage permits rapid and accurate adjustment of the nozzle-to-specimen distance at abrading angles from 20° to 90°. The specimen holder and the nozzle assembly with its adjusting parts are housed in a rectangular brass chamber with a transparent plastic front door and top.

The spent abrasive particles and coating debris are removed through a vacuum exhaust outlet at one end of the test chamber. Rapid monitoring of the abrasive flow rate is accomplished by a weighing tube that has a rubber diaphragm with a hole to accommodate the nozzle tip at one end and a diaphragm of ordinary filter paper at the other end to permit escape of gas while trapping the abrasive particles.



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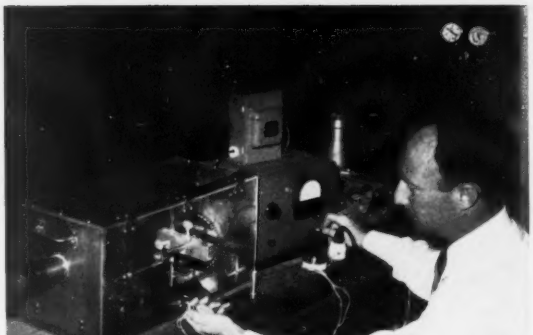


**Abrasive jet equipment developed at NBS for measuring abrasion resistance of an organic coating on metal. Pressurized $CO_2$ blows powder from vibrating storage chamber through a jet nozzle onto test specimen. Time required to abrade through a particular test specimen is a measure of its abrasion resistance depending on such operating conditions as nozzle-to-coating distance, gas pressure, and the angle at which the abrading particles impinge upon the coating, as well as the intrinsic abrasion resisting properties of the coating.**

Although operating conditions can be varied to accommodate extreme differences in materials, it is usually desirable to use a nozzle-coating distance of 0.04 in., a gas pressure of 40 lb/in.$^2$, and a flow rate of 0.15 g/sec, and abrading angles of 90° or 45°. The 90° angle simulates the leading type of erosion encountered by aircraft in flight while the 45° angle simulates scuffing wear which aircraft receive during maintenance operations when they are walked on, struck, or scraped by hose nozzles.

The abrasion time for a given material depends on the test conditions; it increases almost linearly with increasing nozzle-to-coating distance, decreases with increasing pressure, and decreases with decreasing angle of abrasion from 90° down to about 30°. At smaller abrading angles, the abrasion time rises again.

In studies at the Bureau, the abrasive jet method has been found to distinguish significantly between materials difficult to differentiate by qualitative means. Although the degree of correlation with actual service performance has not yet been definitely established, work toward this end is now in progress.

# Frost Closure of Roof Vents in Plumbing Systems

IN THE NORTHERN PART of this country and in Canada, plumbing system roof vents sometimes become partially or completely closed by frost accumulations during very cold weather. Various practical expedients for preventing this phenomenon have been tried, some of which have been successful. For example, some plumbing codes specify a 4 in. minimum diameter for the exposed portion of a roof vent. However, no scientific method for predicting the extent of frost closure under given conditions appears to have been developed until H. N. Eaton and R. S. Wyly of the Bureau conducted an investigation of this problem. The study was sponsored in part by the Housing and Home Finance Agency.

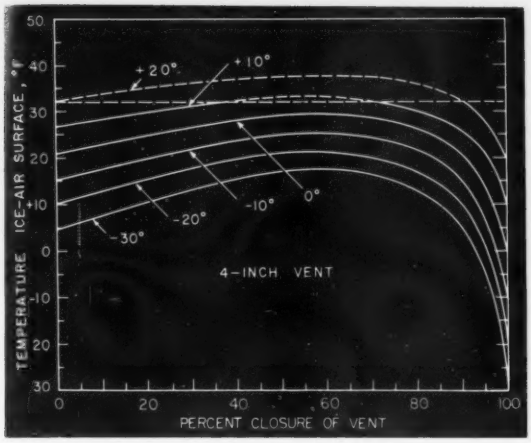
Principal objection to frost closure is the effect created by excessive reduction of the cross section of the roof vent. When this happens, air flow into the vent cannot completely replace the air that is carried down the drainage stack and out of the plumbing system when water is discharged from the fixtures. If the roof vent is nearly or completely closed, the discharge of a single water closet will often suffice to siphon the water seals from one or more fixture traps on the system, thereby making it possible for sewer atmosphere to enter the rooms of the building in which the plumbing system is located.

Frost closure occurs naturally in two forms: (1) A cylindrical layer of frost on the inside of the exposed portion of the vent pipe extending above the roof, and (2) a frost cap at the top of the vent. The two forms may occur simultaneously.

Moisture that produces frost layer or frost cap comes from the stream of warm moist air that ordinarily flows upward through the drainage stack and roof vent in cold weather as a result of chimney action. The column of warm air inside the stack and vent weighs less than a similar column of cold air outdoors; thus the air inside the system rises except when plumbing fixtures are being discharged, at which time the direction of air flow is temporarily reversed.

The exposed part of the roof vent is chilled by the outside air. Hence, as the current of warm moist air rises through the vent, this air is cooled enough so that part of its moisture condenses. Some of the droplets of condensed moisture are carried out of the vent with the air stream while others strike the wall, where they freeze if the temperature of the inner surface of the vent is below the freezing point of water. Thus, the water that freezes on the wall of the vent builds up a layer of frost or ice that increases in thickness as long as the temperature of its inner surface remains below 32° F.

Because the temperature of the air stream in the roof vent is higher than that of the outside air, heat flows radially outward from the vent. According to the NBS study, this transfer takes place in four distinct

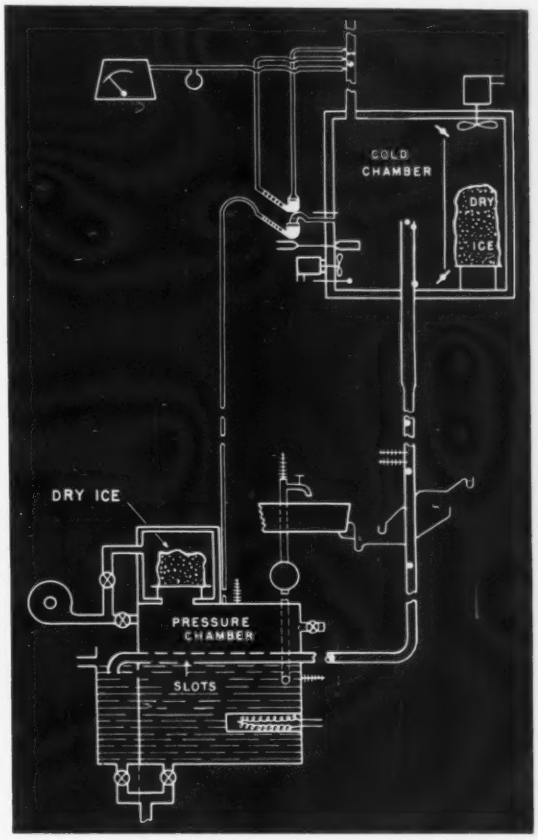



**By means of heat-transfer analysis carried out at NBS on problems of frost closure of roof vents in plumbing systems, it is possible to compute temperature of ice-air surface as vent freezes up for any assumed conditions. Graph shows results of this computation for a 4-in. metal vent, when wind velocity is 10 fps across roof and air stream temperature in vent is 60° F. For an outside temperature of less than 7° F, vent will freeze solid; for higher outside temperatures, it will not. Numbers on curves indicate outside air temperatures. Percentage of closure on horizontal scale is expressed in terms of diameter.**

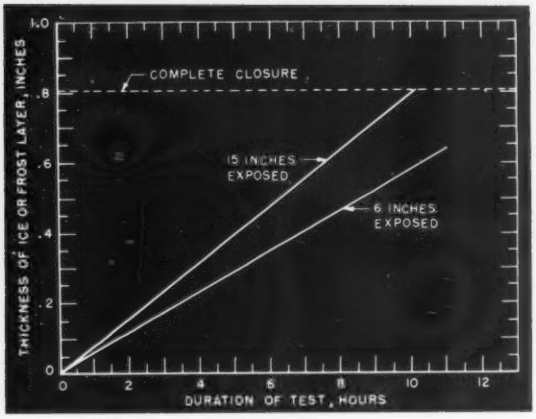
steps: (1) From the air stream in the vent to the ice-air surface; (2) from the ice-air surface through the ice layer to the inner wall of the vent; (3) through the wall of the vent; and (4) from the outer wall of the vent to the atmosphere. An analysis of this process of heat transfer indicates that the heat liberated by the freezing of the water droplets must be taken into account. The velocity of the air stream in the vent and of the wind blowing across the roof must also be considered as well as the thickness and thermal conductivity of the ice layer and the vent. It has been commonly believed that if the weather is cold enough to initiate the process of frost closure in a vent of any diameter and that if these conditions persist for a sufficiently long period, the vent will become completely closed, but this is not always true. Actually, under some conditions a layer of ice or frost forms on the wall of the vent and increases in thickness up to a certain maximum value, depending on the diameter of the vent and on the rate at which heat is extracted from the air stream through the wall of the vent. This thickness may or may not be sufficient to close the vent.

By applying the heat transfer analysis to a set of assumed conditions, it is possible to compute the temperature of the ice-air surface as the vent freezes. For a 4-in. metal vent, a wind velocity of 10 fps across the roof, an air stream temperature in the vent of 60° F, and an outside air temperature of less than about 7° F, the vent will freeze solid, but for outside temperatures greater than about 7° F it will not. For example, if the outside temperature is 10° F, the computations indicate that freezing will stop when the diameter of the opening is reduced to about 0.63 of its original value, while for an outside air temperature of 20° F no reduction whatever will take place. Although the analysis indicates the controlling conditions and the extent of frost closure, it does not show the length of time required to close the vent opening to any particular size.

Frost closure has been produced experimentally in the Bureau laboratories. Roof vents of several different diameters were extended up into a chamber in which temperatures as low as −30° F were maintained, and warm moist air was blown up through the drainage stack and roof vent to simulate the conditions that cause frost closure in actual service. Periods in excess of 9 hr were generally required to close 1½-in. vents exposed to a temperature of −30° F, and increasing the diam-




**Frost closure has been produced experimentally at NBS with the apparatus shown here. It simulates a stack-vented, single-story-with-basement system, complete with water closet, bathtub, lavatory, and kitchen sink. Roof vents of several different diameters were extended up into a chamber in which temperatures as low as −30° F could be maintained, and warm moist air was blown up through the drainage stack and roof vent to reproduce the conditions that create frost closure in actual service.**




**Results of NBS laboratory experiments to produce frost closure of roof vents show that periods in excess of 9 hours are generally required to close 1½ in. vents exposed to an outside temperature of −30° F. Increasing diameter of vent or decreasing length exposed to low temperature increases time required for effecting complete closure. Graph shows average data obtained on 1½ in. vents.**

eter of the vent or decreasing the length of vent exposed to the low temperature increased the time required for effecting complete closure.

Recorded observations of frost closure under service conditions in Canada for 6- and 8-in. vents were found to agree rather closely with the predictions of the Bureau's analysis. The Canadian field data are limited in scope and some of the conditions which may have determined the results are not known; therefore these data probably do not provide a sound basis for judging the degree of accuracy of predictions made by theoretical means. However, these data indicate that the method used in the analysis should give an approximation of the extent of frost closure in service under various conditions. The study also indicates the desirability of keeping the extension of the vent above the roof as short as practicable, of increasing the diameter of the roof vent 1 or 2 sizes over the diameter of the stack, and of using insulating materials around the roof vent in areas where extremely cold weather may be expected.

*For further technical details, see* Frost closure of roof vents in plumbing systems, *NBS Building Materials and Structures Report 142, available from the Superintendent of Documents, Government Printing Office, Washington 25, D. C. for 25 cents.*

# Design Criteria for Mutual Inductance Transducers

SINCE the mutual inductance transducer was originally developed by M. L. Greenough [1] of the Bureau, the device has found increasing application at the Bureau in electronic distance measuring instruments. The transducer detects extremely minute changes in the position of a nearby conducting plate and can be made to record such changes with an accuracy of 5 percent or better. This useful characteristic, together with ease of calibration, has led to its adoption in a number of noncontacting displacement gages for both static and vibratory types of measurements. Examples include an electronic micrometer, a manometer, an oil film thickness indicator, a vibration pickup calibrator, and others.[2]

Until recently design analysis of the transducer has been restricted to its immediate use in a particular instrument. However, there has been a growing need for general design criteria for use in future applications. To provide the necessary data, H. M. Joseph and N. Newman of the Bureau's electronic instrumentation laboratory have made a detailed study of the device's operating principles with major emphasis on transducers using highly conducting reference plates. Their investigation was carried out as part of a program of basic instrumentation sponsored at the Bureau by the Office of Naval Research, the Air Research and Development Command, and the Atomic Energy Commission. The results include a number of design recommendations for obtaining optimum combinations of

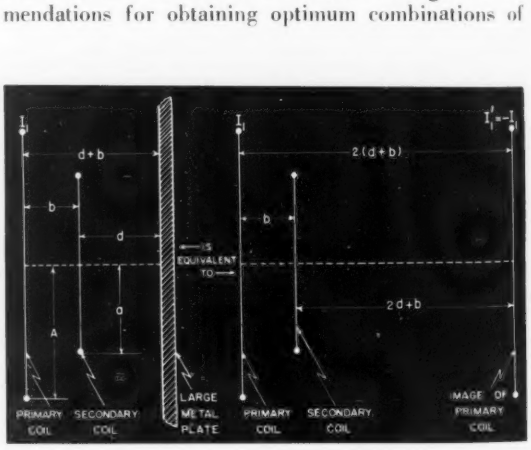
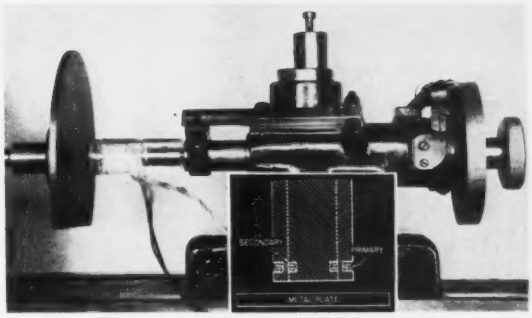



**Diagram demonstrating theory of images used in the design analysis of mutual inductance transducers with highly conducting reference plates. At left is system of two coils and plate: at right is equivalent system of three coils, where the reference plate is replaced by the image of the primary coil. Equivalence of electrical and magnetic effects between the two systems allows use of image coil in mathematical analysis of flux-linkage variations.**




**Experimental setup of the NBS mutual-inductance transducer. Plate at left is reference surface; coils are wound on plastic form. Graduated wheel at right measures changes in surface-to-coil distance. Mutual inductance between the two coils changes with distance and can be detected and indicated through suitable electronic circuitry. *Inset:* Schematic of a typical probe. Both primary and secondary coils are fixed with respect to each other. Metal reference plates may be vibrating provided that highest mechanical frequency is less than the electrical frequency of the current energizing the primary coil.**

stability, sensitivity, and linearity over the range in which the instrument is to be used.

A typical mutual-inductance probe contains two coplanar, coaxial coils wound on a dielectric core. An rf source that is regulated with respect to the product of the frequency and the current energizes the primary coil. The a-c voltage induced in the secondary coil then depends on the distance from the probe to the reference plate. Suitable electronic circuitry detects and amplifies the output voltage from the secondary coil, and this voltage is indicated on a calibrated meter that gives the change in probe-to-surface measurement in inches or centimeters. The instrument is adaptable to very rapid displacement changes; detection of these changes is limited only by the response of the amplifier and by the energizing frequency applied to the probe.

Results of the NBS investigation show quantitatively the change in mutual inductance between two coils when a conducting plate moves toward or away from the coils. The change in mutual inductance can be calculated by use of the theory of images whereby the conducting plate is replaced by an "image coil" that has the same effect as the plate on the mutual inductance between the two coils. Thus, a system of three coils is substituted for the system of two coils and plate. The equivalence of electrical and magnetic effects between the two systems allows the use of the image coil in mathematical analysis of the flux-linkage variations. One of the assumptions in this analysis is that the plate is perfectly conducting; in practice, however, plate conductivity is finite. Although detailed studies of finitely conducting plates have not yet been made, preliminary investigations indicate that in most applications the effect reduces the instrument's sensitivity by only a negligible amount if a sufficiently high frequency is used.

## Design Recommendations

From the analysis made so far, the following design recommendations can be specified:

(1) Reference plate should be as nearly a perfect conductor as practicable.

(2) Primary or exciting coil should be larger than the secondary coil to permit greater heat dissipation.

(3) If it is not possible for the primary coil to be coplanar with the secondary coil, then the primary should be the farther coil from the plate.

(4) Excitation frequency should be as high as possible, provided that the instabilities of resonance are avoided. Although it is true that operation at resonance will greatly enhance the sensitivity, a high degree of sensitivity is not usually a ruling consideration in probe design.

(5) Leads to the primary coil and to the secondary coil should be shielded from each other or should be fixed with respect to each other.

(6) Number of ampere-turns on the primary should be as large as possible.

(7) Number of turns on the secondary should be as large as possible provided that resonance effects are avoided.

(8) Ratio of the secondary coil radius to the primary coil radius should be as large as possible.

(9) Primary coil should be as large as possible. However, for linear response with displacement, it should not be larger than the reference plate.

All of these recommendations refer to probes designed for static measurements. However, no error results from using static considerations when making measurements on vibrating reference plates if the highest mechanical frequency is less than the electrical frequency.

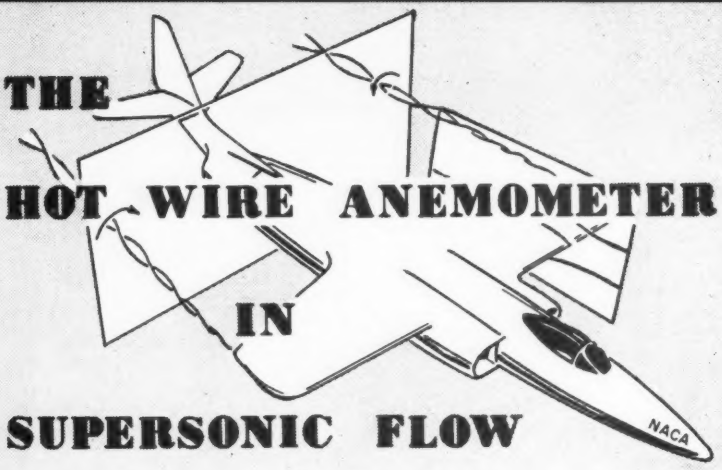
Another aspect of the investigation has been the application of electrodynamic similitude to reduce the amount of experimental work required for the design and construction of probes. Electrodynamic similitude is a method for changing design parameters of a given dimension (such as length or plate conductivity) by a scale factor so that the original output voltage can be maintained by properly altering all parameters of other dimensions. Scaling thus permits a probe of convenient size to be used for experiments instead of one which is too large or too small for ease of handling or fabrication.

[1] Technical details of an electronic micrometer, *Electronics* **20,** *11 (November 1947).*

[2] Electronic micrometer, *NBS Technical News Bulletin* **31,** *37 (April 1947);* Micromanometer, *NBS Technical News Bulletin* **34,** *137 (October 1950);* Oil film thickness indicator, *NBS Technical News Bulletin* **35,** *120 (Aug. 1951);* Electronic sensing of mercury column height, *NBS Technical News Bulletin* **36,** *26 (February 1952);* Vibration pickup calibrator, *NBS Technical News Bulletin* **37,** *181 (December 1953);* A shaft displacement indicator, *NBS Technical News Bulletin* **38,** *70 (May 1954).*

*For further technical details, see* Eddy-current mutual inductance transducers with high-conductivity reference plates, *by H. M. Joseph and N. Newman, Trans. AIEE (in press).*

# THE HOT WIRE ANEMOMETER IN SUPERSONIC FLOW



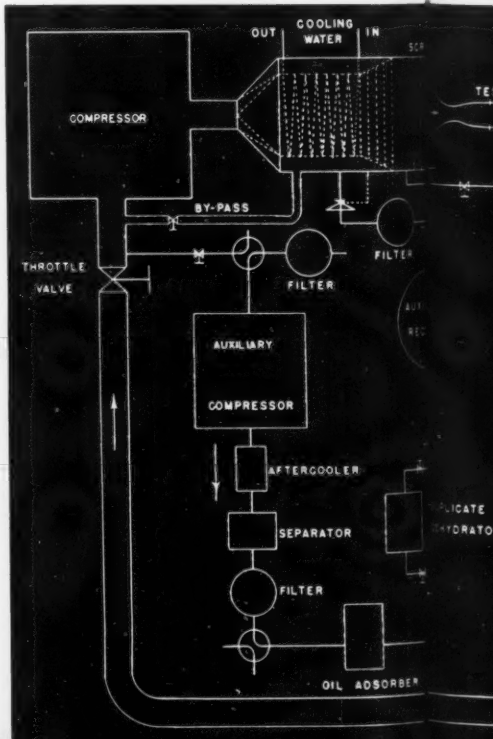

IN RECENT YEARS the development of high-speed jet- and rocket-powered aircraft has stimulated extensive research into supersonic phenomena related to aeronautical design. Beyond the sonic barrier, conditions and forces encountered in air flow are vastly different from those experienced at lower speeds, and basic scientific knowledge must be provided to meet the needs of design engineers.

In all studies of fluid flow, the chaotic motions known as turbulence play a key role. The mixing action of turbulence is one of the controlling factors in the maximum lift of an airplane wing. It is also one of the factors contributing to air friction on the aircraft. Within the subsonic range, the hot-wire anemometer—essentially a very fine electrically heated wire whose resistance changes with air cooling—has been widely used in wind-tunnel studies of turbulence. However, as yet there is no well defined method for studying turbulence at air speeds exceeding that of sound.

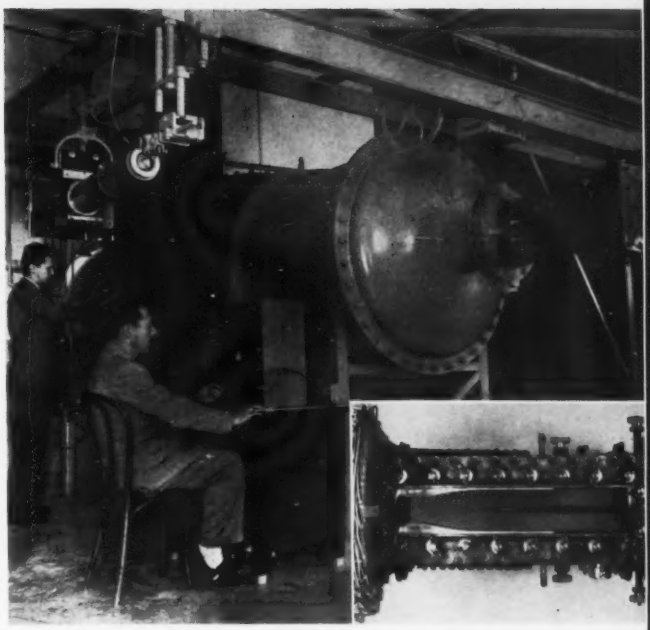
Seeking to extend the range of the hot-wire anemometer into the supersonic region, W. G. Spangenberg of the National Bureau of Standards recently made a study of the behavior characteristics of this instrument at air speeds up to twice the speed of sound. Sponsored by the National Advisory Committee for Aeronautics, the investigation covered a wide range of speeds, air densities, and wire temperatures for wires of different sizes set at various orientations to the stream. In this way new possibilities in the application of the hot-wire anemometer to aerodynamic studies were revealed. The Bureau's results, in combination with those of other laboratories, indicate that the device has broad potentialities as a tool for research on turbulence at high speeds.

In fluid flow, turbulence is usually found in various degrees superposed on the main fluid motion. The flow in wakes and near body surfaces, where turbulence is self-generated, is termed turbulent flow. The forces on a body differ greatly depending on whether the flow near its surface is laminar or turbulent. The free stream at some distance from objects and stream boundaries is not defined as turbulent, but it generally carries with it residual turbulent motions which are instrumental in determining whether the flow about a body in the stream will be laminar or turbulent. Thus, whether near a body or in a free stream, turbulence is an important quantity which must be specified and therefore measured.

The ability of the hot-wire anemometer to respond to rapid variations in velocity has made it useful for




**Schematic diagram of the Bureau's supersonic wind tunnel. Air from compressor is first expanded and cooled before it enters test section through narrow nozzle. Resulting change in cross-sectional area increases velocity in test section and reduces turbulence. Damping screens within expanded portion upstream of test section also aid in reduction of turbulence in test section. Auxiliary compressor and receiver systems control the density of air within tunnel.**



**A portion of the NBS supersonic wind tunnel, showing equipment used in studies of hot-wire anemometer at supersonic air speeds. Hot-wire probe is mounted in glass-sided test section at upper right. Heat loss of hot wire under various experimental conditions is determined by electrical equipment in foreground. Stagnation temperature is measured on thermometer just left of test section while pressure is controlled and measured on panel at extreme left. The camera suspended from ceiling at upper left is used, in conjunction with a light source on other side of test section, to make schlieren pictures of air flow within test section. Investigation indicates that hot-wire anemometer should prove a useful tool for study of nature of supersonic flow. *Inset:* Close-up of the test section in supersonic wind tunnel. Direction of air flow is left to right.**

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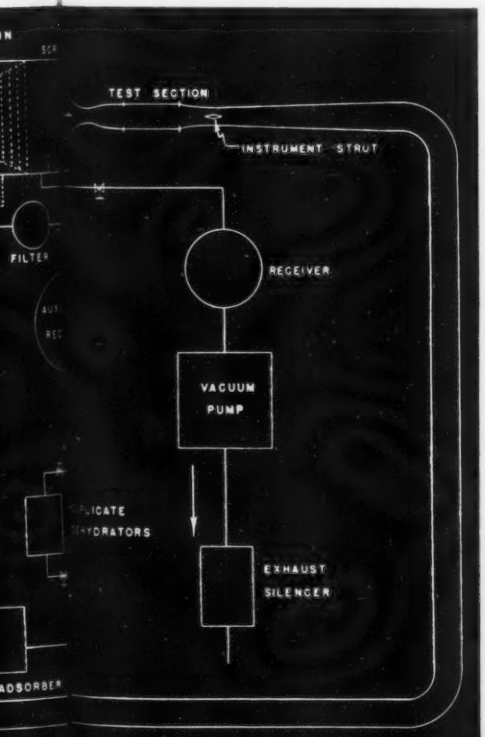
many years in measuring turbulence at low subsonic speeds in terms of magnitude and frequency of velocity fluctuations. However, at high subsonic and supersonic speeds the situation is much more complex than at low speeds. The frequency range must be extended from about 10,000 cps to the order of 100,000 cps. Also, because of compressibility effects and the expenditure of large amounts of power in supersonic wind tunnels, fluctuations of density and temperature occur along with velocity fluctuations. All of these factors contribute in one way or another to the aerodynamic behavior of a model in a supersonic wind tunnel, and to a degree yet unknown, to the behavior of bodies in flight. The object of the NBS investigation was to determine the response characteristics of the hot-wire anemometer to all of the known variables associated with turbulence at high speeds.

The experimental work was carried out in the Bureau's supersonic wind tunnel, which is of the continuously operating, variable-density type with a 3- by 4-inch test section. The stagnation pressure (pressure in reservoir preceding the test section) of the tunnel may be varied from ⅓ to 2½ atmospheres, and its temperature may be regulated at any value between 70° and 140° F.



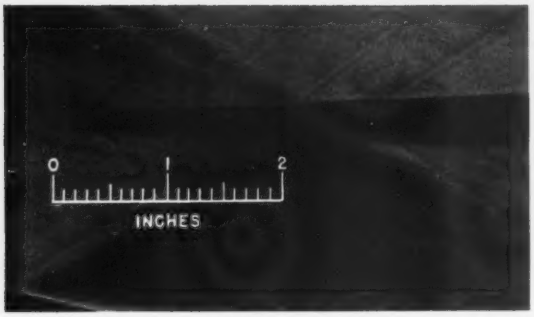

## Experimental Investigation

Free-stream density and velocity and wire diameter were varied independently over the widest possible range so that the role of each in heat loss could be determined. However, since supersonic flow does not permit the velocity at a given Mach number [1] to be varied without varying the free-stream temperature, the effects of Mach number, free-stream velocity, and air conductivity could not be evaluated independently. To reduce the number of variables, all data were run at a constant stagnation temperature. The values of free-stream density, Mach number, viscosity, and conductivity were computed for supersonic flow from the measured stagnation pressure and temperature, assuming isentropic expansion; and for subsonic flow from stagnation pressure, pressure differential between stagnation and test section conditions, and stagnation temperature.

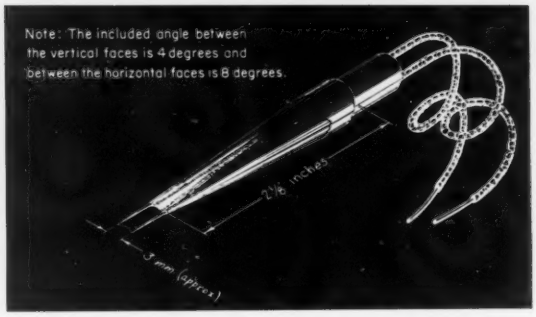
Because of the high frequencies anticipated at supersonic speeds, wires as small as 0.00005 inch in diameter were studied. The wires were made of platinum, tungsten, and platinum-rhodium; their diameters ranged from 0.00005 to 0.0015 inch.

The Bureau experimented with several types of hot-

[1] *The Mach number is the ratio of the actual velocity of the air stream to the local velocity of sound.*




**Schlieren photograph of flow in test section with probe in place. Fine heated wire is suspended between two points on left end of probe. Note shock waves, which appear as light and dark diagonal streaks against grey background.**


Note: The included angle between the vertical faces is 4 degrees and between the horizontal faces is 8 degrees.
2⅛ inches
3 mm (approx.)

**Perspective drawing of special hot-wire anemometer probe developed by NBS to withstand large stresses and vibrations imposed by supersonic flow. Two honed sewing needles which support the hot-wire are butt-brazed to electrical leads imbedded in hard rubber.**

wire probes in an effort to find a design sufficiently rigid to withstand the stresses and vibrational forces encountered in the transonic speed region and during the passage of the shock wave produced by starting and stopping the tunnel. In the design finally adopted, the heated wire was attached to the ends of two honed sewing needles, 0.018 inch in diameter, butt-brazed to electrical leads embedded in hard rubber. To minimize the end-loss correction, the spacing of the needles was usually selected to accommodate a wire about 3 mm long. The wire holders were held by a chuck attached to a 3-directional traversing shaft extending forward into the test section from a diamond-shaped strut farther downstream.

Evaluation of the heat loss from the wires required accurate measurement of wire resistance and current. The unheated resistance was found by using a bridge current sufficiently small to avoid heating the wire. The temperature rise of the heated wire was then determined from the resistance change and the temperature coefficient of the metal. The pressures and pressure differentials were measured with either vertical or inclined manometers, depending upon their magnitude, and temperature was measured with a mercury thermometer. The wire lengths were determined to the nearest hundredth of a millimeter with an ordinary traveling microscope.

## Hot-Wire Characteristics

The accepted theory of incompressible flow indicates that the Reynolds number of the heated wire and the temperature difference between the wire and the ambient air are the principal parameters governing heat loss from the wire. This implies that air density and velocity and wire diameter are equivalent physical variables. However, the results of the Bureau's investigation indicate that in contrast to this accepted theory, the heated wires respond differently to each of the factors contributing to the rates of cooling, such as the velocity and density of the air and the temperature and diameter of the wire, so that no simple relationship can be established.

It was found that wire diameter and air density are effectively equivalent variables, but that velocity or Mach number (the effects of which could not be separated) influence the heat loss entirely differently. When density and wire diameter were held constant, an increasing Mach number was accompanied by a decreasing sensitivity to velocity change. In fact, this sensitivity actually became negative under certain conditions as the speed of sound was approached in the subsonic region. These Mach number effects were found to be less at supersonic speeds, and they tended to disappear as a Mach number of 2 was approached. However, no data were obtained above this speed.

It was also found that the heat loss does not vary directly as the temperature difference between the wire and the air. The heat loss per degree may either increase with temperature loading, depending upon air density, Mach number, and wire temperature and diameter. Wires inclined to the wind direction showed heat losses dependent upon the component of velocity normal to the wire. They displayed supersonic characteristics in a supersonic stream only when this normal component was supersonic.

The NBS investigation thus provides some insight into the many different behavior patterns of the hot-wire anemometer in the supersonic velocity range. While these apparently introduce additional complexities, they are also evidence of the versatility of this instrument for determining those other aspects of supersonic turbulence—such as air density and temperature—which fluctuate along with velocity. Studies of the hot-wire anemometer in the supersonic range are continuing at the Bureau. It is hoped that the supersonic characteristics of the instrument may now be exploited to provide a better understanding of the factors comprising turbulence in compressible flow.

*For further technical details, see* Heat-loss characteristics of hot-wire anemometers at various densities in transonic and supersonic flow, *by W. G. Spangenberg, NACA Tech. Note (in press).*

# A Study of Cellular Concretes

DURING RECENT YEARS the increasing interest of American industry in the manufacture and use of cellular concretes has led the Bureau to study the properties and composition of these light-weight construction materials. The Bureau's program, conducted by R. C. Valore, Jr., of the NBS structural engineering laboratory, has included both a laboratory study of cellular concretes made with domestic ingredients and a comprehensive survey of literature on European cellular concretes to provide information for American builders.

Low density in cellular concretes is attained by the incorporation of a homogeneous void or cell structure throughout the material. The voids may occupy from 25 to 75 percent of the total volume of the hardened concrete, and the density of the concrete may range from less than 20 to more than 100 lb/ft$^3$. However, most European cellular concretes weigh 25 to 50 lb/ft.$^3$ or about one-sixth to one-third as much as ordinary concrete.

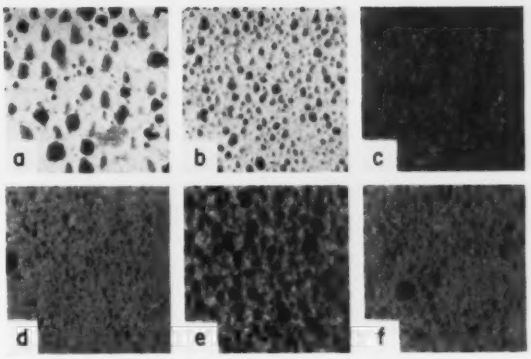
Production of moist-cured and high-pressure steam-cured precast products of cellular concretes has grown rapidly in Europe in the last 20 years. In Sweden the annual production of precast elements exceeds one million cubic yards. Germany, Norway, Russia, Israel, and other countries have plants in operation. Most of the structurally important types of cellular concrete products have consisted of precast roof plank, block, beams, and other elements and have been cured in autoclaves in high-pressure steam.

There are a number of methods for producing the cell structure in cellular concrete. These include:

(1) Mechanical methods, whereby air is entrained in the mixture by the high-speed mixing of a cementitious slurry with a "foaming" or "air-entraining" agent, or where a stable, preformed "air-foam" is incorporated or blended into a premixed slurry. Foaming agents may be of the hydrolyzed protein type used for making air-foams to combat gasoline fires, or they may be rosin soaps, certain detergents, or other organic agents.

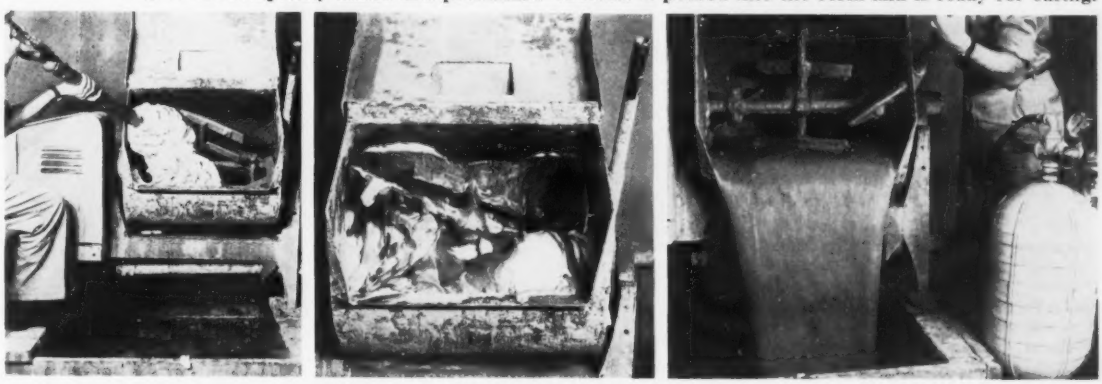
(2) Chemical methods, which depend upon admixtures that react chemically with each other or with certain compounds already present in the cementitious slurry, to generate uniformly distributed gas bubbles throughout the mix. The most widely used agent in the commercial production of "gas" concretes is aluminum powder, which reacts with alkalies in the cementitious mixture to generate hydrogen.[1] Alternatively,

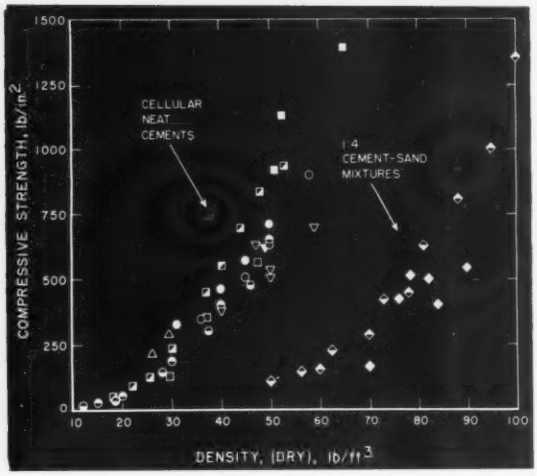
[1] *J. W. Aylsworth and F. L. Dyer, U. S. Patent 1,087,098 (1914).*




**One-inch squares of the ground surfaces of various cellular concretes using different aggregate materials. Density ranges from 35 to 45 lb/ft.$^3$ (a) A Swedish cement-silica autoclaved concrete made with aluminum powder; (b) a mix-foamed, autoclaved cement-silica made in the NBS laboratories; (c) Swedish autoclaved lime-shale material made with aluminum powder; (d) NBS mix-foamed autoclaved cement-expanded shale kiln dust; (e) moist-cured neat cement made with aluminum powder; and (f) autoclaved cement-expanded slate kiln dust made by mix-foaming at NBS.**

**Preparation of a prefoamed cellular concrete using air-foam as an "aggregate." A quantity of air-foam containing a definite volume of air is blended without change in volume into a premixed slurry of pozzolan, cement, and water. *Left:* the foam is injected from the foam generator directly into the mixture; the quantity of foam is gaged by the duration of delivery. *Center:* the foam is blended into the mix. This part of the process does not take more than 2 minutes. *Right:* the completely mixed and prefoamed concrete is poured into the form and is ready for curing.**






**Compressive strengths of a number of moist-cured cellular neat cements (no aggregate) and 1 : 4 cement-sand mixtures. The samples were tested 28 days after making. Data were collected from several sources, including manufacturers' sales literature and NBS studies. Symbols represent different types of mix. Despite differences in test specimens and testing procedures, general relationships between strength and density are indicated.**

hydrogen peroxide and bleaching powder (calcium hypochlorite) may be used to generate oxygen.

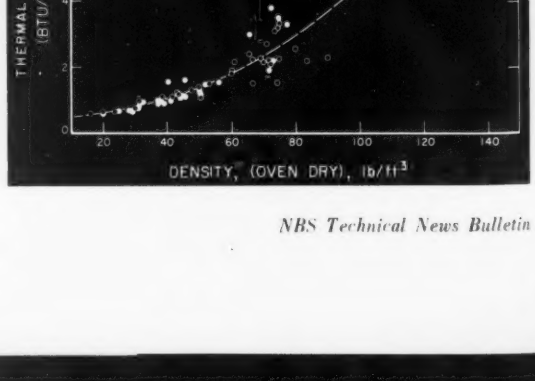
(3) Excess water methods, where a thin slurry is prepared from finely divided cementitious and aggregate materials with several times the amount of water usually required for an equal volume of sand-gravel concrete. Upon curing in high-pressure steam (autoclaving) and then drying, this material acquires a low density by evaporation of excess water and the consequent formation of finely divided voids. Materials made by this process are often called "light-lime" concretes because lime is the usual cementitious ingredient.

The choice of aggregates for cellular concretes usually depends on the type of curing. For curing at ordinary temperatures or in steam at atmospheric pressure, concrete sand or plaster sand may be used; the aggregate may be omitted entirely for materials of the lowest densities.[2] In mixtures cured in these ways the cementitious ingredient is usually portland cement. The Bureau's studies showed that moist-cured mixtures without aggregate usually have been limited to nonstructural thermal-insulation applications because the cement content and drying shrinkage are undesirably large at densities high enough to produce structurally adequate material. At a given density, moist-cured cement-sand cellular concretes usually had lower strength or higher shrinkage and weight than some lightweight-aggregate concretes.

For a given weight the autoclaved types of cellular concrete have a greater strength; and essentially complete development of strength may be obtained in less than 1 day. The steam pressure in the autoclave is usually in the range 120 to 160 lb/in.² (350° to 370° F) and is maintained for 6 or more hours. Mix for autoclaved cellular concretes includes both a cementitious and siliceous material. The siliceous material or pozzolan should be comparable in fineness with portland cement, or considerably finer than ordinary sand aggregate and may comprise a large proportion of the mix without detrimental effects. The cementitious ingredient may be portland cement, hydrated or unslaked lime, or a blend of cement and lime. During autoclaving, the pozzolan reacts with hydrated lime in the presence of moisture to form calcium silicates that have relatively low drying shrinkage and high strength. The reactions involved are similar to those occurring in the sand-lime brick, also cured in high-pressure steam.

Some industrial wastes abundant in this country are high in silica and alumina. These include fly ash from coal-burning power plants and from kilns producing expanded lightweight aggregates made from shale, slate, and clay. Some of these materials were used with portland cement in autoclaved cellular concretes prepared at NBS. Commercial European products are made with lime or portland cement and burnt oil shale, ground silica sand, fly ash, or other pozzolans. Both the European commercially-made materials and those prepared at the Bureau had, at a density of 35 to 50 lb/ft.³ compressive strengths of 300 to more than 2,000 lb/in.², flexural strengths of one-third to one-fifth of these values, and drying shrinkages of 0.02 to 0.10

[2] *The term "cellular concretes" does not include concretes made with lightweight aggregates. For paper describing NBS study, see* Lightweight aggregate concrete, *by R. W. Kluge, M. M. Sparks, and E. C. Tuma, J. Am. Concrete Inst.* **20,** *625 (May 1949).*




**Relationship of thermal conductivity to density for moist-cured and autoclaved cellular concretes of various compositions and made by different processes. (Data from 17 different sources and NBS investigations.) In the range from 20 to 60 lb/ft.³ thermal conductivity is a close function of density, despite the many sources of data and possibly different types of specimens and test conditions.**

TABLE 1. *Properties of some autoclaved "gas" and "foam" concretes*

| Density, oven dry | Compressive strength | Flexural strength | Drying shrinkage | Absorption (volume) | Thermal conductivity |
|---|---|---|---|---|---|
| *lb/ft³* | *lb/in.²* | *lb/in.²* | *%* | *%* | *Btu/hr/ft² (°F/in.)* |
| 30 | 300 to 500 | 100 to 150 | 0.02 to 0.08 | 25 to 40 | 0.8 |
| 40 | 600 to 1,200 | 200 to 300 | 0.02 to 0.08 | 25 to 40 | 1.0 |

For "light lime concrete" made by excess water method, strength and absorption values may be considerably higher than values shown for "gas" and "foam" concrete.

percent, depending upon the nature and proportions of cementitious and pozzolanic ingredients.

Nonautoclaved cellular concretes containing nonaggregate have developed 0.3 to 0.6 percent linear drying shrinkage and 200 to 400 lb/in.² 28-day compressive strengths at dry densities of 30 to 40 lb/ft³. Cement-sand mixtures (1:4 by weight) weighing 70 to 90 lb/ft³ had 28-day strengths of 250 to 800 lb/in.² and shrinkages of 0.08 to 0.20 percent. In addition to the advantage of light weight, cellular concretes have relatively high thermal insulation values—10 to 15 times that of commonly used sand-gravel concretes.

*For further technical details, see* Cellular concretes, part 1 and 2, *R. C. Valore, Jr., J. Am. Concrete Inst.* **25,** *Nos. 5 and 6 (May, June 1954). Also available as a reprint from the American Concrete Institute, 18263 W. McNicholos Road, Detroit 19, Michigan, at a cost of $1.00. This paper has been awarded the Wason Medal by the American Concrete Institute. This award is made annually to the "most meritorious paper" published in the latest volume of the Proceedings of the American Concrete Institute.*

# Publications of the National Bureau of Standards

Journal of Research of the National Bureau of Standards, volume **54,** number 2, February 1955 (RP2566 to RP2571 incl.). Annual subscription $4.00.

Technical News Bulletin, volume **39,** number 2, February 1955. 10 cents. Annual subscription $1.00.

CRPL–126. Basic Radio Propagation Predictions for May 1955. Three months in advance. Issued February 1955. 10 cents. Annual subscription $1.00.

### Research Papers

*Reprints from the Journal of Research, volume* **54,** *number 2, February 1955. Single copies of the Journal vary in price. Single copies of Research Papers appearing in the Journal are not available for sale. The Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C., will reprint 100 or more copies of a Research Paper. Request for the purchase price should be mailed promptly to that office.*

RP2566. Geometric factors in electrical measurements relating to corrosion and its prevention. W. J. Schwerdtfeger and Irving A. Denison.

RP2567. Pore-size distribution in collagen and leather by the porosimeter method. Robert R. Stromberg.

RP2568. Collagen pores determined by electron microscopy. Max Swerdlow and Robert R. Stromberg.

RP2569. Effect of low temperatures on the mechanical properties of a commercially pure titanium. Glenn W. Geil and Nesbit L. Carwile.

RP2570. Reactions at wet-dry interfaces on fibrous materials. Robert Schaffer, Wm. D. Appel, and Florence H. Forziati.

RP2571. Scintillation spectrometry of low-energy bremsstrahlung. Margarete Ehrlich.

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C554. Cheyenne Mountain tropospheric propagation experiments. A. P. Barsis, J. W. Herbstreit, and K. O. Hornberg. 30 cents.

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# TECHNICAL NEWS BULLETIN

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